SSERVI-ESF14-022

Author: DAVID BLEWETT

POSTER

Dust / Regolith

Lunar crustal magnetic anomalies: Natural laboratories for space plasmas and geology

The Moon does not possess a global internally generated magnetic field. However the lunar crust contains areas of magnetized rock, tens to a few hundred kilometers in size. Many of the magnetic anomalies are located at the antipodes of major impact basins. The magnetic anomalies are also associated with highly unusual bright surficial markings known as lunar swirls. The origin of the magnetic anomalies and the bright swirl features is uncertain, though the observed correlation is very strong. There are several hypotheses for the origin of the swirls. These include atypical space weathering caused by stand-off of the solar wind, unusual dust accumulations or regolith texture related to electric fields associated with the magnetic anomaly, and scouring by cometary meteors, gas, or dust. The magnetic anomalies and swirls present a natural laboratory for investigation of several major areas in planetary science, including: (1) Planetary magnetism: What is the source of the magnetic anomalies? Are they related to an actively generated early lunar dynamo and/or to effects of large basin-forming impact events? Is the magnetized body an igneous intrusion, a deposit of magnetized basin ejecta, or a relatively thin surficial layer?(2) Lunar geology and space weathering: What is the nature and origin of the lunar swirls? The lunar magnetic anomalies potentially allow us to control for one of the key variables, solar wind exposure.(3) Plasma interactions with strong gradients in fields: What are the electric potentials, ion trajectories, and consequences for weathering of an airless silicate body with small-scale magnetic fields? What are the implications for backscattered particles and exosphere production by surface sputtering?

Author: DANIEL BRITT

ORAL

Dust / Regolith

Forward Modeling Space Weathering

Introduction: Space weathering is a generic term for the effects on atmosphereless solid bodies in the solar system from a range of processes associated with direct exposure to the space environment. The classic example of space weathering is the formation of the lunar spectral red slope associated with the production of nanophase Fe (npFe0) in the lunar regolith. But our understanding of the processes and products of space weathering has been limited by our access to pristine samples like the lunar soils and our necessarily limited view of surfaces provided by telescopic remote sensing. We have primarily focused on the most obvious aspects of weathering, such as the lunar red slope, but our limited data has also limited our view of this essentially physical and chemical phenomena. However, there is another way to explore space weathering that is not limited by observations or avail-able pristine samples. Space weathering can be viewed as the response of surface materials to inputs that drive the surface composition away from equilibrium, resulting in chemical reactions can be understood from the underlying thermodynamic driving forces. Using techniques and insight developed by materials science physics, especially related to surface science, we can assess the environment of the common asteroidal and planetary materials and forward model the expected results of the weathering reactions. This approach can help us understand the formation processes of known weathering products, predict the formation of other products, and identify already well-known materials as the products of weathering reactions. A General Theory of Space Weathering: Space weathering can be viewed as driven by a combination of the chemical environment of space (hard vacuum, low oxygen fugacity, solar wind implantation of hydrogen) along with thermal energy supplied by micrometeorite impacts. The forward modeling of space weathering as thermodynamically-driven decomposition of common rock-forming minerals suggests the production of a range of daughter products: (1) The silicate products typically lose oxygen, other volatile elements (i.e. sulfur and sodium), and metallic cations, producing minerals that are typically more disordered and less optically active than the original parent materials. (2) The decomposed metallic cations form in nano-sized blebs including npFe0, on the surfaces or in condensing rims of mineral grains. This creates the powerful optical component seen in the lunar red slope and also creates an environment for catalyzing further reactions.(3) The liberated volatile elements and gases (O, S, Na) may form an observable exosphere if sufficient quantities are available, and can either escape from the body or recombine with solar wind implanted hydrogen to form trace amounts of water and OH. Mineral decomposition can be thought of as the first stage of space weathering. It produces weathered surfaces somewhat depleted in volatile elements, creates a predictable set of minor or trace minerals, and leaves the surfaces with catalytic species, primarily npFe0. However, a second stage of further reactions and weathering depends upon the presence of "feedstock" components that can participate in catalyzed chemical reactions on exposed surfaces.

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Dust / Regolith

Peroxy as a Marker for Ancient Water, a Biohazard, and Dynamic Terminator Processes.

Water ice, condensed over time out of the vapor phase into permanently shadowed craters, is present on the moon. What about "ancient water"? It was there when the moon formed 4+ GYrs ago, at least in form of hydroxyl, such as O3Si-OH, in nominally anhydrous minerals. However, decades of studying lunar rocks from the Apollo era have led experts to believe that the moon is "dry" (where "dryness" is defined as absence or near-absence of O3Si-OH and the absence or near-absence of H). We challenge this view.Marker for Ancient WaterIn nominally anhydrous minerals most hydroxyl pairs disappear by way of a redox conversion in which the two hydroxyl oxygens transfer an electron to their respective protons: O3Si-OH HO-SiO3 _ O3Si-OO-SiO3 + H2. The two H form H2, while the donor oxygens, now in the valence O–, form a peroxy bond. As H2 is diffusively mobile, it can outgas. Left behind are peroxy as a "memory" of the former hydroxyl content. Therefore, if one sets out to find evidence for the "ancient water" on the moon, one must look – not for H or OH – but for peroxy. It is possible that peroxy will reveal a much greater reservoir of ancient water than has been previously detected.Source of Possible Biohazard for Human ExplorationWhen peroxy dissociate, they release highly mobile positive hole charge carriers, h•. Positive holes are defect electrons in the oxygen anion sublattice, chemically equivalent to O– in a matrix of O2–, which can also be written as •O radicals, known and feared for their highly oxidizing properties. In addition, due to their positive charge and mutual repulsion, positive holes accumulate at surfaces, edges and corners of finely comminuted regolith particles. Thus they could do extensive oxidative damage to the skin, mucous and lung tissues of future astronauts. Detectable Dynamic Terminator ProcessesIt is not yet known whether lunar rocks contain peroxy, we can design experiments to test it. When peroxy release positive holes, h•, these electronic charge carriers are highly mobile. They can flow out of the volume, where they were activated. They spread out at speeds around 100 m/sec over distances of meters to kilometers. Peroxy break-up is achieved by impact and by UV light. Hence, at the lunar morning terminator, h• charges will spill out of the illuminated surface over the surface still in shadow. Recombination of h• to peroxy leads to spectroscopically distinct IR emission, possibly also to a release of excited O atoms glowing at 630 nm, a process that might be important to understand in the context of emission of O atoms from the lunar surface. It may also be possible to detect a change in radar albedo between sunlit and shadowed conditions for the same surface.For landed missions, we propose to measure changes in electric ground potential and in electrical conductivity associated with the UV activation of the h• charge carriers at the morning terminator as a function or regolith depth.

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Dust / Regolith

Lunar Lightning : The Need for Multi-Physics Modeling of the Impact Process

Up until now, the process of impacts on the Lunar surface has largely been considered as a kinematic process. We believe that it is time to consider the role of electromagnetic forces in the evolution of the impact as well as the novel chemical and physical processes that may evolve as the result of large currents in the ground and ejecta. We propose a three phase impact process that will require multi-physics modeling to understand and analyze.Phase 1) the kinematic evolution of bulk solids (this is well understood)Phase 2) large subsurface currents produced by the pressure wave of impact (seen in terrestrial Earthquakes)Phase 3) Development of plasma discharge in ejecta column (in analogy to hypervelocity impacts)Magnetic signatures are associated with some relatively young lunar impact craters [Halekas et al., 2003], though nothing is known about the orientation of the magnetic field vectors. Some craters show features, which suggest a powerful vertical electric discharge. We propose mechanisms by which (i) a halo of remnant magneti-zation would form through a powerful positive hole current pulse flowing outward upon impact, (ii) an large vertical electric potential would develop between the plasma plume and the impact crater. Both mechanisms are based on the discovery of a previously unrecognized type of defects, ubiquitous in all terrestrial igneous rocks and probably also in lunar rocks: pairs of defect electrons associated with the O2– sub-lattice, forming tightly coupled, electrically dormant peroxy such as O3Si-OO-SiO3. When activated by stress, the peroxy break up releasing positive hole charge carriers, highly mobile defect electrons h• associated with energy levels at the upper edge of the valence band. Terrestrial gabbro, when loaded within <1 msec, has been shown to produce positive hole outflow currents equivalent to ~109 A km-3. Such large currents may be crucial to understand the magnetic signature around lunar impact craters. At the same time, a strong electric field will build up between the negatively charged crater and the vertical plume, pointing to the possibility of a powerful lightning discharge through the electrically conductive plasma of the plume. The presence of positive hole charge carriers has far-reaching implications for the moon and other solid solar system bodies.The plasma interaction could range from dynamic chemical processes resulting in regolith and volatiles exposed to sunlight in the heated and charged ejecta plume to the possibility of very large plasma discharges of energies comparable to the impact itself. In any event, there is strong evidence that the effect of electromagnetic and plasma processes and chemistry my play a here to for unrecognized role in the evolution of impacts and them chemical evolution associated with gardening.Halekas, J. S., R. P. Lin, and D. L. Mitchell (2003), Magnetic fields of lunar multi-ring impact basins, Meteoritics &Planetary Science, 38(4), 565-578.

Author: BRADLEY DE GREGORIO
POSTER

Dust / Regolith

Aberration Corrected STEM Characterization of Glass Analogs for Regolith Grains on Airless Bodies

Space weathering of regolith particles on airless bodies leads to formation of nanophase Fe metal and amorphization of silicate minerals in the top ~100 nm of the grain surfaces (Keller and McKay, 1997, GCA 61, 2331-2341). Such changes can have a drastic effect on the optical properties of these bodies, in effect masking their true mineralogy and composition. Making a quantitative link between the atomic-to-nanoscale effects on the particles, and the macroscale properties is essential for maximizing the science return from exploration of airless bodies and returned samples. As part of the RIS4E collaboration, we are performing aberration-corrected scanning transmission electron microscopy (STEM) on analog samples to determine the atomic-scale structural and chemical effects of space weathering. Our samples consist of a series of basaltic glasses of varying composition and Fe oxidation state. The new Nion UltraSTEM 200 currently being installed at the Naval Research Library will permit quantitative energy dispersive X-ray spectroscopy (EDS) at scales down to single atom detection, and Fe oxidation state determination from measuring the relative intensities of the Fe^{2+} and Fe^{3+} L-edge peaks with electron energy loss spectroscopy (EELS) at an energy resolution of 0.3 eV. These nanoscale measurements will be coordinated with synchrotron X-ray absorption near-edge structure (XANES) spectroscopy of the same samples to extend the analyzed volume to the macroscale. In addition, principal component analysis (PCA) algorithms developed for analysis of the XANES spectra will be applied to the EELS data in order to identify characteristic spectral channels that are sensitive to changes in oxidation state (in addition to the typical Fe^{2+} and Fe^{3+} peaks).

Author: BRETT DENEVI

ORAL

Dust / Regolith

Global Variability in Regolith Properties on Vesta

The Dawn spacecraft spent nearly 14 months in orbit around 4 Vesta, mapping the asteroid with a framing camera (FC), a visible and infrared mapping spectrometer (VIR), and Gamma Ray and Neutron Detectors (GRaND). Despite differences in the depth of sensitivity of each instrument, most of our remote sensing information about Vesta comes from its regolith. Regolith is a mixture of local material comminuted by numerous small impacts, material excavated by distant impacts, plus a small contribution of exogenic material. Knowledge of the origin, depth, and mobility of Vesta's regolith is thus of consequence for a contextual understanding of results from each of Dawn's instruments.We investigate Vesta's regolith with several methods developed previously for the Moon and asteroids that can provide depth constraints, and taken together can provide a fuller picture of Vesta's regolith. These morphologic methods include assessing the presence or absence of coherent material within a crater's ejecta, examining crater walls, studying morphologic evidence for downslope movement and infilling of topographic lows with regolith, and documenting the preservation of small craters (formed mostly within the regolith) at different locations. The combined results from these methods are then compared to predictions of regolith depth based on the ejecta distribution expected for a model crater production function.From these studies, we find evidence for substantial regional variability in Vesta's regolith. A large equatorial region from ~100–240° E (Claudia system) contains a relative dearth of craters <10 km in diameter that have excavated blocky material, suggesting a regolith thickness >~1 km thick, or a more mobile regolith which can more rapidly bury blocks. This area also contains fewer craters that expose material resistant to erosion in their walls, and has a lower retention of small craters (<~300 m) that formed largely within the regolith. These features are consistent with a thicker-than-average regolith in the region, which is marked by a low albedo and relatively high hydrogen abundance. A thicker regolith in this region is consistent with the suggestion that the low albedo and high hydrogen are due to the accumulation of exogenic, carbonaceous debris in ancient, well-preserved regolith. This is in contrast to the Rheasilvia basin, with high albedo and low hydrogen, where we find a high concentration of blocky craters, exposures of material resistant to erosion in craters walls, and a larger population of small impact craters. These results are compared to numerical models of regolith production. Potential sites are identified where local bedrock may be exposed and the spectral properties of these sites are explored.

Author: GENEVIEVE DEVAUD

Dust / Regolith

ORAL

Asteroid Regolith Mechanical Properties: Laboratory Experiments with Cohesive Powders

We are conducting laboratory experiments to investigate the role of cohesion in governing regolith processes and geomorphological expression on small solar system bodies. Our goals are to develop an improved understanding of the geomorphological expression of granular media in the microgravity environments of regoliths on small asteroids and to quantify the range of expected mechanical properties of such regoliths.Many previous experimental results with cohesive powders have been obtained under ambient atmospheric conditions and we are reproducing some of those measurements for the sake of comparison. In the space environment the minimum distance between particles can be much closer than is possible on Earth, where atmospheric gases, water vapor, and relatively low temperatures allow for significant contamination of surfaces. In the extreme environment of space, surfaces are much 'cleaner' due to the lack of adsorbed molecules on the surfaces of materials, allowing for closer effective distances between surfaces so that the dipole-dipole interactions between molecules in the particle surfaces can come into play. Recognizing the significant role of surface contaminants and trapped air in cohesion and column failure, the bulk of our experiments are done under vacuum (mTorr) with previously vacuum baked powders in order to more closely simulate the environment and surface properties on an airless body. In the simulation side, we are using a Soft-Sphere Discrete Element Method code to replicate the results obtained with glass micro-spheres and as a means of validation. Simulations will allow us to control or remove some of the experimental constraints such as the confining walls, the uncertainty of the packing process and the strength of cohesive bonds. This will also allow us to better understand the failure mechanisms and their interplay with material properties. The environmental chamber for our experimental work resides at Ball Aerospace & Technologies Corporation (BATC) in Boulder, Colorado. Within the chamber our powder samples are manipulated within confined transparent walls to create piles and columns of powders that we can then tilt or otherwise interact with to induce sloped failures, faults and fractures, and other morphological features that provide data on the self-cohesive forces at play. The powders used in our experiments include JSC-1A, 3-micron glass microbeads, and, for familiar context, ordinary unbleached white flour.In addition to examining and quantifying the morphology of faults and fractures in our powder columns and piles and the angles at which slope failures occur, we have to date noted with interest that the talus slopes resulting from the collapse of the columns and piles often contain a number of distinct 'boulders' formed from self-cohered 'clods' of the powder material. The superficial resemblance of these 'boulders' to the coarse fraction of the regolith in regions of the surfaces of Eros and Itokawa suggests that some care be applied in interpreting all such large fragments on these objects as necessarily composed of competent hard rock.

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Dust / Regolith

Engineering surfaces to shed particles: A solution to a dusty problem?

Tenacious adhesion of dust to surfaces in the vacuum environment of space is viewed as one of the biggest obstacles to exploration and scientific discovery on the Moon, Mars and asteroids. Mitigating particle adhesion is also costly and difficult during semiconductor or optics processing on earth. Particle adhesion on surfaces is a complex, poorly understood phenomenon in spite of many years of study. On the surface of an airless body, adhesion is mediated predominantly through van der Waals and Coulombic interactions due to charging by the solar wind, and highly reactive, clean surfaces. Over the last ten years at Ball Aerospace & Technologies Corp (BATC), we have demonstrated the effectiveness of an ion beam process that dramatically reduces the adhesion of lunar simulant dust to quartz, glass, Kapton, Teflon and silicon surfaces in dry, ambient, and vacuum environments. We call this the STAR process, for Surface Treatment for Adhesion Reduction. STAR silver-coated Teflon coupons performed well in a head-to-head comparison of three competing types of dust mitigating surfaces in a space-simulated environment at NASA Glenn Research Center. Cooled substrate materials were bombarded with ions generated by a commercially available Kaufman ion source approximately 2 feet away. After ion beam treatment we deposited different types of dust onto the surface, including JSC-1AF lunar simulant, JSC MARS-1A Martian simulant, silica spheres, high Ti basalt, aluminum oxide and calcium oxide powders. We deposited dust by sieving a monolayer onto the surface, or by dumping dust by the spoonful to simulate different types of deposition. Effectiveness of dust removal was monitored optically and reported as percent area coverage following removal by centrifugal detachment or by tapping and gently blowing with nitrogen gas, respectively. As an example, virgin silicon surfaces retain 22% PAC of dust after removal, as compared with 1% PAC dust coverage after removal from STAR surfaces. This performance has been retained over several years of exposure to ambient environments and repeated dusting. Atomic force microscopy is the gold standard for evaluating surface structure, and we found that surface roughening on an Ångstrom-level scale was found to correlate well with reduced adhesion. Contact angle hysteresis was also found to be an effective process tool for evaluating effectiveness of dust adhesion reduction. The large difference in advancing and receding contact angles reflects topological and/or chemical heterogeneity. We found that contact charge transfer between the particles and STAR surfaces was not consistently different from that of the virgin surfaces. The extent of contact charge transfer is notoriously variable, even between "identical" materials. This method of reducing adhesion of particles to surfaces is particularly attractive for optical or thermal control materials as the intrinsic properties of the material are maintained. This method could also be nicely paired with the highly effective electrodynamic screen to reduce voltage requirements.

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Dust / Regolith

ORIGIN AND EVOLUTION OF REGOLITH ON AIRLESS BODIES: THE ROLE OF THERMAL FATIGUE

The surface of planetary bodies is of interest as it is the part observed with remote sensing instruments, and the part that will be sampled by sample return missions. Images obtained through space missions [1,2], infrared and radar observations [3,4] and returned samples [5] re-veal these surfaces are covered by a layer of loose, unconsolidated, debris referred to as 'rego-lith'. Understanding the formation and evolution of regolith as well as the variation of these pro-cesses will provide insight into the origin, age, and properties of these bodies.Regolith generation and evolution is typically attributed to re-accumulation of ejecta as well as continuous micrometeoroid impact leading to the breakdown of boulders [6, 1]. While this model can explain lunar regolith, it may not be applicable to kilometer-sized asteroids. Im-pact velocities on main-belt asteroids (~5km/s) are much lower than on the Moon (~15 km/s) and are therefore less efficient in shattering asteroidal rocks. Laboratory experiments [7] and impact models [8] show that crater ejecta velocities tend to exceed the escape velocity of asteroids. An alternative mechanism of regolith formation is fracturing due to thermal fatigue by diurnal cy-cling. Such a phenomenon was noted as a mechanism for fracturing of rocks in cold and hot ter-restrial environments [9]. Dombard et al. [10] attributed the formation of ponds on Eros to ther-mally disaggregated boulders, and Delbo et al. [11] demonstrated the importance of thermal fragmentation for regolith production and surface rejuvenation on asteroids. Thermal fragmenta-tion also has the effect of weakening surface rocks, thus increasing the efficiency of rock commi-nution by micrometeoritic impact.This study aims to characterize the thermal fragmentation by examining its viability in producing regolith. Thermal fragmentation is studied as a function of temperature range, rate, petrology, grain size, and size-frequency distribution of the resulting particles. It is noted that areas of lunar permanent shadow [12] provide the potential to test the relative importance of thermal fragmentation models. These areas do not experience a diurnal thermal cycle; thus, fragmentation would be exclusively due to micrometeorite bombardment. Surface properties and fragment distributions can be measured and compared with areas that experience thermal cycling. In this context, fatigue experiments will be conducted to provide the necessary input parameters for the thermal fragmentation mechanism in a regolith formation and evolution model. Digital Image Correlation (DIC) will be used to obtain full-field strain maps as a consequence of fatigue crack growth, and these strain maps will be used to help determine the driving force on the crack tip. The recorded images by DIC technique will be also utilized to measure fatigue crack growth rate.

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Dust / Regolith

Dust cleaning, transportation and sampling in lunar environment using traveling electric field

Unlike Earth, moon does not have a magnetic field to protect it from high energy particles emitting from the Sun. Once they reach the surface of the moon, they penetrate into the dust particles and remove their electrons leaving them positively charge on the day side. On the dark side electron plasma makes the surface negatively charged in the order of thousands of volts. Since the materials composing regolith have low conductivity and there is no atmosphere on the moon, the dust particles tend to keep their electrical charge. The charge particles repeal themselves and hover above the surface. From Apollo documents all the lunar surface activities inversely affected by highly abrasive and electrically charged dust particles which cover everything they come into contact with. In this study, the possibility of using electrostatic and dielectriphoretic forces in dust removal from rover equipments is addressed. Electrodes placed parallel to one another shaping planar, cylindrical, and spherical configurations connected to a voltage source generating a traveling electric field which applies force to the charged particles and move them along or against the field. Applied frequency, voltage amplitude and shape, inclination angle, and particles shapes are the parameters their influence were examined on cleaning efficiency of the device. The results show this technique can remove 75 to 95 percent of the accumulated dust on surfaces.Furthermore, applications of traveling electric field in transporting dust particles between two points, e.g. moon surface to an on-board lab, and separating and sorting particles based on their electrical charge s and mass for geotechnical sampling and examinations were investigated.

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Dust / Regolith

Spectral and Thermophysical Properties of Phobos from the Mars Global Surveyor Thermal Emission Spectromete

The spectral properties of Phobos have been previously investigated at both visible/near-infrared and mid-infrared wavelengths. These works have shown that Phobos spectra include a broad 0.65 micron feature that may be attributable to Fe-bearing phyllosilicates or Rayleigh scattering by nanophase metallic Fe particles. VNIR spectra of Phobos also include a 2.8 micron metal-OH feature that may be diagnostic of desiccated phyllosilicates or solar wind-induced hydroxylation of the Phobos regolith surface. At mid-IR wavelengths, Phobos displays a variety of spectral classes, which are consistent with tectosilicates, such as feldspars and mixtures of phyllosilicate minerals. In this work, we re-evaluate MIR spectra of Phobos acquired by the Mars Global Surveyor (MGS) Thermal Emission Spectrometer (TES) experiment. We gathered TES spectra from four early mission TES aerobraking orbits (orbits 476, 501, 526, and 551) and culled the data to include only the highest temperature daytime observations of the Phobos surface. For the surface of Phobos, subpixel temperature mixing is clearly an issue. Therefore, we modeled the radiance of the surface as a linear combination of blackbodies of many different temperatures. The resulting emissivity spectra occasionally have emissivity values greater than unity, but are not affected by strong slopes due to surface anisothermality.Surface emissivity spectra of Phobos display a variety of spectral shapes while having some features in common. Most spectra display a strong drop in emissivity shortward of the Christiansen Feature (CF), typical of finely particulate silicates. Average spectra all have modeled CFs in the 8.34 to 8.4 micron range, indicating an olivine/pyroxene-dominated surface if the surface is optically immature (devoid of space weathering). It has been shown for the Moon, however, that optically mature surfaces have CF positions that tend to be shifted by ~0.2 microns to longer wavelengths compared to optically immature surfaces of the same composition. Assuming the average surface of Phobos is optically mature, corrected CF positions of 8.14 to 8.2 microns indicate a more feldspar-rich surface. This is consistent with VNIR observations, which lack strong 1 and 2 micron Fe^{2+} absorption features and longer wavelength MIR transparency features that are consistent with finely particulate tectosilicates such as feldspar. Nearly all spectra display emissivity maxima at ~6 microns, consistent with varying levels of surface hydration. This hydration feature may be due to water bound in minerals or transient water formed through interaction of the solar wind with the Phobos surface. The relatively strong 6 micron features found in the TES data are somewhat surprising due to the lack of a strong 3 micron water band in VNIR observations of Phobos. Finally, some spectra display emissivity maxima at ~6.7 microns, which has been shown to be consistent with small amounts of carbonates intimately mixed with silicates. This observation may support the hypothesis that Phobos is a captured D-type asteroid, similar in composition to the Tagish Lake meteorite, which is carbonate-bearing.

SSERVI-ESF14-033

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Dust / Regolith

Dynamical and Collisional Timescales of Meteoroids Released From Jupiter Family Comets

Large dust particles (meteoroids) released from comets are initially spread along the orbit of their parent body. This spreading is caused by variations in the initial release conditions of the particles, such that they have slightly different orbital periods to their parents. Close planetary encounters (mostly by Jupiter) scatter meteoroids through interplanetary space. Simultaneously collisions with interplanetary meteoroids shatter cometary meteoroids and generate large amounts of smaller fragment particles. An understanding of the importance of these three mechanisms is required to determine how a meteoroid stream disperses into the interplanetary background. To this end, we compare the timescales for spreading, scattering, and shattering of meteoroids released from Jupiter family comet 67P/CG. Jupiter family comets currently provide a major source of meteoroids to the interplanetary complex. Their orbits are characterized by frequent encounters with Jupiter. Comet 67P/CG is a typical member of this class of comets. The initial spreading of meteoroids is calculated by studying the initial velocities of the particles. The effect of Jupiter scattering is simulated on a string of particles along the comet's orbit. The timescale of planetary scattering is compared to the timescale imposed by the Poynting-Robertson effect. The effects of shattering are determined for meteoroids of masses 10^-6, 10^-3, and 1 g. By applying the ESA IMEM meteoroid model (Dikarev et al., 2005, Advances in Space Research 35:1282) to meteoroid stream particles at various positions along their orbit we calculate their collisional lifetimes, and compare them with timescales for spreading, scattering, and shattering. Our results have implications for the total lifetime of meteoroid stream particles that originate from Jupiter family comets.

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Dust / Regolith

Dynamical and Collisional Timescales of Meteoroids Released From Jupiter Family Comets

Large dust particles (meteoroids) released from comets are initially spread along the orbit of their parent body. This spreading is caused by variations in the initial release conditions of the particles, such that they have slightly different orbital periods to their parents. Close planetary encounters (mostly by Jupiter) scatter meteoroids through interplanetary space. Simultaneously collisions with interplanetary meteoroids shatter cometary meteoroids and generate large amounts of smaller fragment particles. An understanding of the importance of these three mechanisms is required to determine how a meteoroid stream disperses into the interplanetary background. To this end, we compare the timescales for spreading, scattering, and shattering of meteoroids released from Jupiter family comet 67P/CG. Jupiter family comets currently provide a major source of meteoroids to the interplanetary complex. Their orbits are characterized by frequent encounters with Jupiter. Comet 67P/CG is a typical member of this class of comets. The initial spreading of meteoroids is calculated by studying the initial velocities of the particles. The effect of Jupiter scattering is simulated on a string of particles along the comet's orbit. The timescale of planetary scattering is compared to the timescale imposed by the Poynting-Robertson effect. The effects of shattering are determined for meteoroids of masses 10^-6, 10^-3, and 1 g. By applying the ESA IMEM meteoroid model (Dikarev et al., 2005, Advances in Space Research 35:1282) to meteoroid stream particles at various positions along their orbit we calculate their collisional lifetimes, and compare them with timescales for spreading, scattering, and shattering. Our results have implications for the total lifetime of meteoroid stream particles that originate from Jupiter family comets.

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ORAL

Dust / Regolith

LUNAR IMPACT EJECTA CLOUDS OBSERVED BY LDEX

The Lunar Dust Experiment (LDEX) onboard the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission successfully mapped the spatial and temporal variability of the dust size and density distributions in the lunar environment. LDEX reliably detected and measured the mass of submicron and micron sized dust grains, while in lunar orbit from 10/6/2013 - 4/17/2014. LDEX also measured the current from low-energy ions and collective charges from dust impacts that are below the detection threshold for individual dust detection, enabling the search for the putative population of grains with radii ~ 0.1 micron lofted over the terminator regions by plasma effects. LDEX has identified and characterized the dust ejecta cloud that is maintained by the sporadic micrometeoroid bombardment of the lunar surface. The density of the dust ejecta cloud increases with decreasing altitude, and shows significant enhancements during meteor showers. LDEX found no evidence of the plasma-lofted particles, and put strict new upper limits on the density of the high-altitude small grains. _The discovery and detailed understanding of the lunar ejecta cloud opens new pathways to learn about the dust populations comprising the sporadic background and the meteor showers, as well as the response of the lunar regolith as function of the mass and speed of the bombarding particles. The collected data will be further used to improve dust hazard models for the near-Earth environment. Ejecta clouds, similar to that observed around the Moon are likely to be present at other objects that are possible targets for future human exploration: asteroids, and the Martian Moons Phobos and Deimos. An LDEX-type instrument on precursor missions will greatly contribute to the safety of the crew and the mission to these targets.

Author: GEN ITO
POSTER

Dust / Regolith

Calculating the Scattering Properties of Fine-grained Particulates of Planetary Surfaces

Determining the compositions of fine particulates, such as the regoliths of the Moon and near Earth asteroids, has been a problematic task in infrared remote sensing. Difficulty in modeling the scattering properties arises due to the multiple scattering, absorption, and transmission of light that occurs when regolith particles have diameters equal to or smaller than the wavelength of light being used by an instrument. Radiative transfer models have been used to calculate the emissivity of closely-packed, fine particles with some success, but these models cannot fully describe the behavior of emissivity spectra. Although the radiative transfer models have been adjusted to account for closely-packed particles, the physics of radiative transfer only holds for truly well-separated particles. The closely packed nature of planetary regolith particulates may be the fundamental cause of inadequate modeling by various radiative transfer models, and therefore, this study takes a different approach where the scattering properties from a single cluster are calculated in which the cluster is composed of many particles. Scattering by each individual particle is calculated by exactly solving Maxwell's equations at every light and particle interface using the publicly available Multiple Sphere T Matrix code. Then, the cluster-averaged scattering properties of a single volume are input into Hapke's equation for hemispherical emissivity. This approach allows us to correctly calculate the near-field scattering properties of regolith particles to generate a cluster-averaged single scattering albedo. Previous works have shown that this method can generate more accurate emissivity spectra. Following their example, we generated a cluster containing 150 closely-packed spheres of olivine composition with 10 _m diameters. Another cluster composed of spheres with diameter of 100 _m was also generated, but using 10 spheres due to computing constraints. Within a wavenumber range of 100 – 2000 cm-1, correct optical constants of olivine and corresponding scale factors were assigned to the clusters. Using these inputs, we executed the MSTM code on NASA's Pleiades supercomputer located at Ames Research Center. Our work compares the quality of the exact calculation method to those from various scattering models, including Mie theory, the Hapke emissivity model, and a hybrid Mie/Hapke model. Furthermore, we will explore the effects of cluster size, particle size distribution, compositional heterogeneity, and particle shape and compare our model results with laboratory measurements to validate the accuracy of this model.

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Author: THOMAS KEHOE

POSTER

Dust / Regolith

Understanding Asteroid Regolith Properties from the Post-Disruption Evolution of Dust Bands

We have performed dynamical modeling of the structure of a faint dust band observed in carefully co-added IRAS data at an ecliptic latitude of 17º that convincingly demonstrates that it is the result of an extremely recent (significantly less than 1 Ma ago) disruption of an asteroid and is still in the process of forming. Our detailed modeling of the 17º partial dust band has led to a new understanding of the information that is preserved in these young structures about the original source body and the disruption process. In particular, we show that young dust bands retain information about both the size distribution and cross-sectional area of dust released in the original disruption, before it is lost due to orbital and collisional decay.As a result of this modeling, we can confidently link the 17º partial dust band with the Emilkowalski cluster based not only on its ecliptic inclination but also on its node, semimajor axis, and its age, which we show to be consistent with the value of 220 ±30 ka determined for the age of the Emilkowalski cluster by Nesvorny´ et al. (2006). We also found that the inclination dispersion of the dust particles is more than would be expected for a low ejection velocity and that ejection velocities of a few times the escape velocity of the Emilkowalski cluster source body provide a better fit of the models to the observations.We determine that the cross-sectional area of dust currently associated with the band is on the order of 10^6 km2 and the cross-sectional area of dust initially released by the disruption of the Emilkowalski cluster source body is on the order of 10^7 km2. This would correspond to a regolith layer ~3 m deep on the ~10 km diameter source body's surface. We discuss the implications that such a significant release of material has for the temporal evolution of the structure, composition, and magnitude of the zodiacal cloud.For the young 17º partial dust band, we find a lower bound on the cumulative size distribution inverse power-law index of 2.1, for dust particles with diameters ranging from a few µm up to a few cm, indicating that the cross-sectional area of ejected material is dominated by the smallest of these particles. Interestingly, this is a much steeper size distribution than the 1.2 cumulative inverse power-law index found for the older central and 10º bands (Grogan et al., 2001; Espy et al., 2010). This implies that small particles are being removed, as the dust band ages, at a faster rate (due to orbital decay caused by radiation forces) than they are being replenished (due to inter-particle collisions), and that results obtained from modeling older, fully-formed, dust bands will underestimate the contribution of small particles to the original disruption ejecta.

SSERVI-ESF14-038

Author: SASCHA KEMPF

ORAL

Dust / Regolith

PROPERTIES OF THE LUNAR DUST EXOSPHERE AS SEEN BY LDEX

Impacts of fast interplanetary meteoroids with the Lu-nar surfaces produce ejecta particles which populate tenuous, approximately isotropic clouds around the moons. This process is very efficient: a typical inter-planetary 10-8 kg micrometeoroid impacting the Earth' Moon produces a large number of dust particles, whose total mass is about 650 times that of the impactor. The ejecta particles move on ballistic trajectories, most of which have lower initial speeds than the moon's escape velocity and re-collide with the surface, while particles ejected fast enough to escape from the moon's gravity may form tenuous dust rings such as Jupiter's gossamer rings. The Lunar Dust EXperiment (LDEX) on the Lunar Atmosphere and Dust Environment Explorer (LADEE) was the first instrument flown in the vicinity of the Moon, which is sufficiently sensitive to observe the lunar dust exosphere. This talk will report about first insights into the properties of the Lunar dust exo-sphere. The observed scaling of the impact rate with the distance to the Lunar surface is in rough agreement with mean field models of planetary dust exospheres.

Author: JAMIE MOLARO

Dust / Regolith

POSTER

Thermoelastic grain-scale stresses on airless bodies and implications for rock breakdown

Most studies on the thermomechanical breakdown of rocks focus on arid, terrestrial environments where other weathering processes are slow. Propagation of microfractures in rocks occurs due to expansion and contraction caused by changes in temperature, and by mismatches in thermal expansion behavior of adjacent mineral grains. Airless bodies may provide an environment uniquely suited to this process, as many experience large diurnal temperature ranges, rapid changes in temperature during sunrise and sunset, and/or high thermal cycling rates due to rapid rotation. Thermal breakdown of materials has been suggested as an active process on various airless bodies, including the Moon, Mercury, Vesta, Eros, and Phaethon, however the extent of the damage produced as a result is unknown. Historically, the effectiveness of this process has been assessed by rates of surface temperature change, with a threshold of 2K/min required for permanent damage. Here we link surface temperatures and spatiotemporal temperature gradients to actual stresses near rock surfaces in order to better judge the efficacy of thermal weathering on different planetary bodies. In this study, we employ finite element simulations of the thermoelastic behavior of microstructures with varying grain sizes and thermophysical properties. We imposed the solar and conductive fluxes calculated by a 1D thermal model at the surface and at 5 mm depth on a microstructure of mineral grains over one solar day. The microstructure is a randomized grid of hexagonal grains (0.3mm in diameter), 25% of which are assigned properties of plagioclase, and 75% pyroxene. The heat and displacement equations are solved over a solar day on a Lunar equatorial surface. Preliminary results indicate that these surfaces experience a diurnal maximum effective stress (or von Mises stress) of 150 MPa while under tension. This peak stress occurs pre-dawn when the microstructure is coldest, indicating that stresses are predominantly controlled by temperature rather than temperature gradients. Typical tensile strengths of rocks are on the order of 100 MPa, suggesting that thermomechanical fracturing may be possible on the Moon, but not necessarily on other bodies. Similar model runs on Vesta and Phobos produce peak tensile stresses of only 5 and 13 MPa, respectively. Phobos is somewhat unique and experiences a secondary spike in tensile stress of 6 MPa due to a midday eclipse that occurs near martian equinoxes. Examination of the microstructure during the peak tensile state reveals that stresses are concentrated along surface-parallel grain boundaries, suggesting that after temperature, it is the heterogeneity of a rock that dominates its thermoelastic behavior. Examination of the microstructure over time reveals an anti-correlation between high stresses and large spatiotemporal temperature gradients, indicating that rates of surface temperature change are not an effective proxy for stress.We will present model results of thermoelastic stresses induced within microstructures with varying grain properties and distributions for a variety of airless bodies. This work represents the first step in quantifying the contribution of thermal stress weathering to regolith production rates on these bodies.

Author: TOBIN MUNSAT

ORAL

Dust / Regolith

Ice Target and Gas Target Experiments in the IMPACT Dust Accelerator

The dust accelerator facility at the SSERVI Institute for Modeling Plasma, Atmospheres, and Cosmic Dust (IMPACT) is presently implementing two major target upgrades: a cryogenic ice target and a high-pressure gas target. The ice target consists of a LN2 cryogenic system connected to both a water-ice deposition system as well as a movable freezer/holder for a pre-mixed liquid cartridge. Planned experiments include the bombardment of a variety of frozen targets and simulated ice/regolith mixtures, and the assessment of all impact products (solid ejecta, gas, plasma) as well as spectroscopy of both the impact-produced light flashes and the reflected spectra (UV, visible, IR). Such measurements are highly relevant to both physical and chemical surface modification of airless bodies due to micrometeoroid impacts. The gas target consists of a differentially pumped chamber kept at moderate background pressures, such that high-velocity (~10 km/s) micrometeoroids are completely ablated within 10’s of cm (i.e. within the measurement chamber). The chamber is configured with segmented electrodes to perform a spatially-resolved measurement of charge production during ablation, and localized light-collection optics enable an assessment of the light production (luminous efficiency). Such studies are critical to the understanding of past and future ground-based measurements of meteor ablation in Earth’s atmosphere, which in turn can potentially provide the best estimates of the interplanetary dust particle flux

Author: CARLE PIETERS

ORAL

Dust / Regolith

The Special Environment of Lunar Swirls

Lunar swirls are some of the most beautiful and enigmatic features on the Moon. They are characterized by their unusual albedo markings, which are wispy or sinuous in form. Swirls are often associated with the invisible presence of notable magnetic anomalies. They are found without any topographic expression of their own and occur across mare or highland terrain. We have recently re-examined the spectroscopic properties of swirls using data from the Moon Mineralogy Mapper in order to determine whether there are compositional distinctions associated with their bright and dark markings. The data are consistent with the features being locally derived (rather than addition of a significant foreign component), but their albedo variations do not follow any common alteration or mixing pattern for lunar materials. Specifically, the spectral properties of swirls are not consistent with normal ‘space weathering’ of exposed lunar materials that results from the accumulation of nanophase metallic iron on soil grains when exposed to the harsh environment on the lunar surface. Instead, the observed characteristics of swirls argue for a difference in micro-scale texture of swirl regolith structure compared to that of nearby local soils. Some rearrangement of the fine components is also likely at swirls. Important issues to explore in the lunar environment are the effects that a relatively strong local magnetic field may have on small electrostatic forces that control interaction between soil grains. The mobility of the finest fraction is another key question as well as the strong diurnal cycling involving solar radiation and solar wind energetic particles. If we could understand the direct cause and effect between the magnetic anomalies and the character and patterns in these enigmatic swirls, we would go a long way toward constraining the origin of the magnetic signatures themselves – which in turn would ultimately constrain the early history of the Moon.

Author: ANTHONY SHU
POSTER

Dust / Regolith

Cratering Studies in Thin Plastic Films

Thin plastic films, such as Polyvinylidene Fluoride (PVDF), have been used as protective coatings or dust detectors on a number of missions including the Dust Counter and Mass Analyzer (DUCMA) instrument on Vega 1 and 2, the High Rate Detector (HRD) on the Cassini Mission, and the Student Dust Counter (SDC) on New Horizons. These types of detectors can be used on the lunar surface or in lunar orbit to detect dust grain size distributions and velocities. Due to their low power requirements and light weight, large surface area detectors can be built for observing low dust fluxes. The SDC dust detector is made up of a permanently polarized layer of PVDF coated on both sides with a thin layer (≈ 1000 Å) of aluminum nickel. The operation principle is that a micrometeorite impact removes a portion of the metal surface layer exposing the permanently polarized PVDF underneath. This causes a local potential near the crater changing the surface charge of the metal layer. The dimensions of the crater determine the strength of the potential and thus the signal generated by the PVDF. The theoretical basis for signal interpretation uses a crater diameter scaling law which was not intended for use with PVDF. In this work, a crater size scaling law has been experimentally determined, and further simulation work is being done to enhance our understanding of the charge generation from the detector. An electrostatic Poisson relaxation code is used in conjunction with the experimentally determined scaling law to determine the veracity of current theories on charge generation in PVDF detectors. Experimental results and simulation results and conclusions will be presented.

Author: CHAE KYUNG SIM
POSTER

Dust / Regolith

Multi-Band Polarimetric Observations of the Lunar Surface

We carried out multi-band (U, B, V, R, and I passbands) polarimetric observations of the whole near side of the moon from the Lick observatory using a 15-cm reflecting telescope. Polarization of the light scattered by the lunar surface contains information on the mean particle size of the lunar regolith, which gradually decreases by continued micro-meteoroid impact over a long period and thus is an age indicator of the surface. We present a map of the mean particle size for the whole near side of the moon. We also compare our observations with the computer simulations and laboratory experiments that we recently began to conduct.

Author: JONAS SIMOLKA

ORAL

Dust / Regolith

Development of a Gas Impact Chamber for Laboratory Studies of Meteoric Ablation

A gaseous target for hypervelocity dust particles is developed for the laboratory study of micrometeoroid ablation in the Earth's and planetary atmospheres. The dust accelerator facility at LASP, University of Colorado at Boulder is used to accelerate micron and submicron sized dust particles to relevant velocities, > 10 km/s. The gas impact chamber is 40 cm long and is pressurized to 0.02 – 0.5 Torr using dry nitrogen or other gases. At the low end of the pressure range the particles will undergo deceleration due to air drag, and at high end they will completely ablate. There are three main diagnostic methods: (1) There is an impact ionization detector at the end of the chamber that measures the mass of the remaining particle. The timing of the impact yields the impact velocity and the deceleration from air drag. (2) The electrons and ions produced during ablation will be collected on a set of biased electrodes. There are two sets of 16 electrodes arranged along the top and bottom of the particle's path in the ablation chamber. The electrodes are biased to separate the positive and negative charges of the ablation plasma and each electrode is connected to a separate charge sensitive amplifier. These electrodes are the main monitors of the ablation process by detecting the produced charge along the particle's path, determine the ionization probabilities of the ablated material, and observe differential ablation the first time. (3) Photomultiplier tubes are mounted to the chamber to detect the light emitted by the hot particle and its final impact, and monitor the emission from the impact ionization process. The pressure in the chamber is monitored using an absolute vacuum gauge. There is a two stage differential pumping system that connects the ablation chamber to the high-vacuum beam line of the dust accelerator. The talk will present the science motivation and design of this new SSERVI/IMPACT facility, the calibration of the diagnostics, and the first test measurements.

Author: JAMEY SZALAY

ORAL

Dust / Regolith

LADEE/LDEX Observations of Meteor Streams at the Moon

The lunar surface in continually bombarded by meteoroids from a variety of sources. Upon impacting the lunar surface, each meteoroid can produce ejecta plumes with hundreds of times more mass than the incoming meteoroid, lofted 10’s to 100’s of km above the lunar surface. The Lunar Dust Experiment (LDEX) onboard the LADEE mission measures the response of the lunar surface to meteoroid bombardment. For their brief duration, meteor streams can deliver higher impactor fluxes than the continual bombardment by the sporadic background of interplanetary dust particles. During peak shower times, the dust production from the surface can dramatically increase. Of all known meteor showers during the LADEE mission, the Geminids produced the strongest lunar response, for which LDEX observed significantly enhanced fluxes with a strong clustering near the point of maximal Geminids flux on the lunar surface. This talk will present a comparison of the meteor shower activity with the intermittently observed, unusually high impact rates recorded by LDEX. We also report on the differences in the physical properties of the ejecta particles generated during meteor streams and from the sporadic background. Characterizing the response of the lunar environment to known meteor streams will help identify unknown meteor streams in future missions to airless solar system bodies. This will aid in improving hazard estimates were an LDEX-type instrument to fly to future human exploration targets.

Author: LAWRENCE TAYLOR

ORAL

Dust / Regolith

UNDERSTANDING LUNAR SOILS: AN APOLLO PERSPECTIVE

Nine scoops of lunar soil were added to one of the rock boxes during Apollo 11, in order to keep the rocks from "rattling around". This 10 kg of soil was sieved, and the <1 mm fraction was designated as soil 10084, one of the most studied of all lunar samples. Yes, this soil was used in place of the unavailable 'popcorn' for packaging, not as a specific dedicated sampling of soil; and much of the Apollo soils were simply the packing materials. But why is "corporate memory" valuable?In spite of the first Apollo soils coming back in July, 1969, it took almost three (3), yes, 3 years for the nature of the strange magnetic susceptibility of the soil to be figured out – no magnetite; no Fe3+ - our "Terrestrial Hats" led us astray. Native Fe? Yes, the soils had been formed by meteorite and micro-meteorite bombardment = metallic Fe. But, the actual lunar basalts had native Fe as a mineral formed during the normal igneous crystallization. However, the Ferromagnetic Resonance (FMR) analyses detected a strange, at that time unique, Single Domain Fe signature for metallic Fe between 33 and 300 Å (3-33 nm) (Morris, 1974). It was this SD-Fe [IS] that became the symbol for "Soil Maturity", when combined with the total iron in the soil expressed as FeO - "IS/FeO". And the origin of this SD-Fe was speculated as solar-wind reduction of impact-produced melt that effectively 'glued' agglutinates together (Housley et al., 1973). It took an additional 2 decades to solve that actual true formation of this SD-Fe as selective vaporization and subsequent deposition of super-heated soil melt – "reduction" by thermal dissociation (Keller & McKay, 1993). Somewhere over time, in the '90s, the term "nano" became the sexy word of choice, whereby the SD-Fe became "Nanophase Fe" – NP-Fe, but with the loss of peoples' memory that this np-Fe was to be the same as SD-Fe. Was this the remote-sensing community? And then along came the "Synthesizers", who were making lunar soil simulants with NP-Fe in them. But like the SD-Fe in lunar soil that gives the FMR IS signal similar to lunar – the IS/FeO? No way! Even after the $M that have been spent in such endeavors. Is corporate memory valuable? You betchu!

SSERVI-ESF14-047

Author: XU WANG

ORAL

Dust / Regolith

Interactions of a plasma flow with a magnetic dipole field: Implications for large positive lunar surface potentials

Recent in-situ observations, as well as computer simulations, indicate that the lunar surface may be charged to potentials from +150 up to +300 V in magnetic anomaly regions. This is much higher than the generally expected value of ~ +10 V on the dayside surface due to the photoemission. We present new laboratory experiments studying the interaction of flowing plasmas with magnetic dipole fields to address these unexpected observations and modeling results. A plasma flow with an ion energy varying from 10 to 50 eV is created to interact with a magnetic dipole field above an insulating surface. We investigated the case of a moderate strength magnetic anomaly where electrons are magnetized while ions remain unmagnetized. A large positive charge is found on the surface in regions where the ions are collected and the electrons are deflected away. The potential on the surface increases with increasing the energy of the incident ions up to values of +20V. However, this is only observed with the dipole moment oriented perpendicular to the surface. When the dipole moment is parallel to the surface, no large positive charges are found. It is likely that electron-electron collisions cause the electrons to be scattered to the surface and neutralize the positive charge. We will discuss the detailed mechanisms and implications for lunar surface charging. Increasing the energy of ions from 50 eV to 1 keV, using an ion source in the future work, is expected to be capable of reproducing the observed much larger positive surface potentials. Our experimental work, along with in situ observations and computer simulations, will help to advance our understanding of lunar surface processes including the formation of unusual albedo features, dust transport and the production and loss of volatiles.

Author: MICHAEL ZIMMERMAN

ORAL

Dust / Regolith

The solar wind's interaction with a lunar crustal magnetic field: detailed kinetic plasma simulations

We present new 2D simulations of the interaction between the solar wind, the lunar surface, and a km-scale region of isolated crustal magnetization. Results of a simulation to describe the region around local noon, including a subsurface magnetic dipole with a near-surface field strength of 3 _T, show: (1) electron standoff up to 100 m above the surface, (2) protons precipitating onto the surface and creating a >1 kV potential drop and >10 V/m electric field, (3) one or more well-defined, energy-conserving ion jets organized by the strong near-surface electric field, and (4) tenuous populations of ions traveling horizontally along the surface, among many other rich details. This new simulation allows us to characterize the dominant physical processes involved in the solar wind-magnetic anomaly interaction. For example, close attention is paid to the mechanisms that lead to spatial profiles of vertical ion flux and kinetic energy, which are strongly linked to sputtering and space weathering and, hypothetically, lunar swirl formation. These simulations will be useful to inform decisions about future in situ lunar instrumentation.